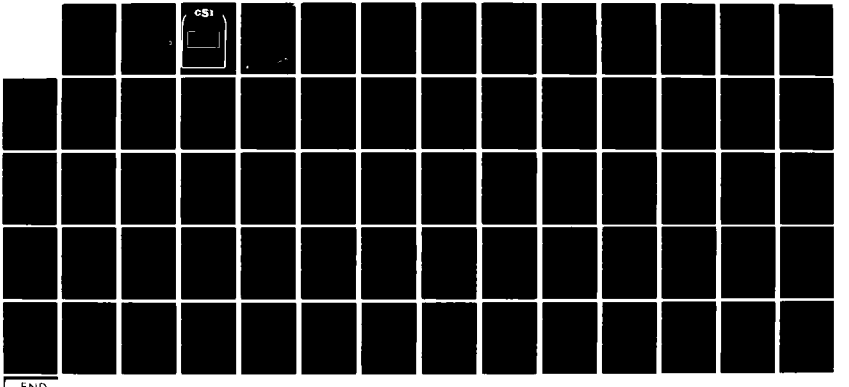
AD-A122 160 RESEARCH IN DIGITAL COMMUNICATIONS(U) UNIVERSITY OF SOUTHERN CALIFORNIA LOS ANGELES COMMUNICATION SCIENCES INST R A SCHOLTZ ET AL. NOV 82 CSI-82-11-01 1/1

UNCLASSIFIED ARO-15943.69-EL DAAG29-79-C-0054 F/G 17/2 NL



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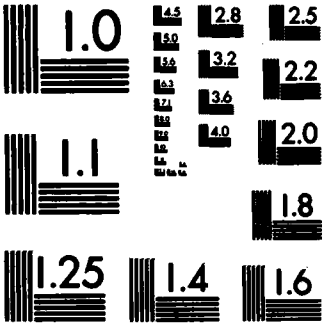

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
15943.69-EL	AD-A122 160	

4. TITLE (and Subtitle)

Research in Digital Communications

5. TYPE OF REPORT & PERIOD COVERED

Final:
15 Mar 79 - 31 Aug 82

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)

R. A. Scholtz
L. M. Silverman

8. CONTRACT OR GRANT NUMBER(s)

DAAG29 79 C 0054

9. PERFORMING ORGANIZATION NAME AND ADDRESS

University of Southern California
Los Angeles, CA 90089-0272

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

11. CONTROLLING OFFICE NAME AND ADDRESS

U. S. Army Research Office
Post Office Box 12211
Research Triangle Park, NC 27709

12. REPORT DATE

Nov 82

13. NUMBER OF PAGES

66

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report)

Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

DTIC
DEC 7 1982
H

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

NA

18. SUPPLEMENTARY NOTES

The view, opinions, and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

digital communications
spread spectrum
burst communications
network synchronization
radar
pulse compression
signal processing

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Research included efforts in several areas of digital communications, namely spread-spectrum code design and sync acquisition, burst communications, network synchronization, radar pulse compression designs, communication over "messy" channels, and certain topics in system theory and signal processing. Significant progress has been made in most of these areas, with virtually none of the proposed problems having been found totally intractable. Throughout the duration of this contract, the reporting objective has been to place research results in the open literature where they will be available to all. Accordingly, this final report consists in large measure of a listing of papers produced under this contract, along with their abstract

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RESEARCH IN DIGITAL COMMUNICATIONS

FINAL REPORT

November 1982

CSI-82-11-01

UNIVERSITY OF SOUTHERN CALIFORNIA
ELECTRICAL ENGINEERING ~ SYSTEMS
LOS ANGELES, CALIFORNIA 90089-0272

RESEARCH IN DIGITAL COMMUNICATIONS

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A Final Report on

Contract No. DAAG29-79-C-0054

with the

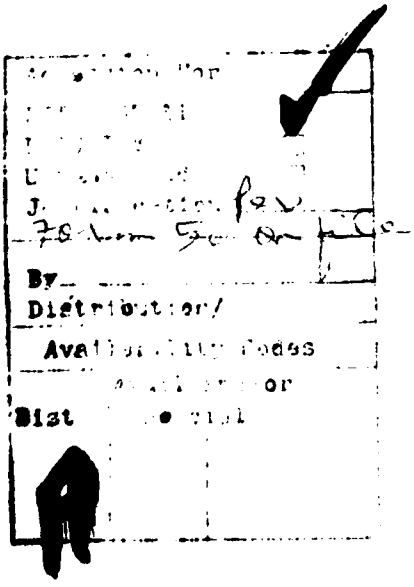
Army Research Office

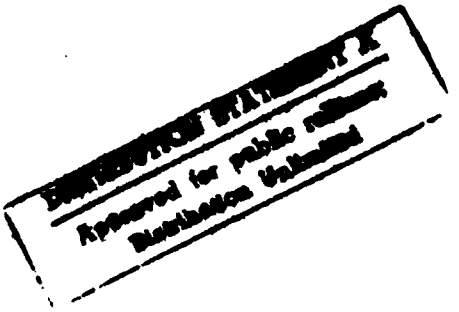
P.O.Box 12211

Research Triangle Park

North Carolina 27709

September 1982





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I. INTRODUCTION

On March 15, 1979, a group of investigators at the University of Southern California began work in digital communications under a large research contract from the Army Research Office. This grant was the outgrowth of efforts to combine several smaller grants for administrative purposes and to encourage collaboration on research problems of significant interest to the Army. This first block contract was for a duration of three years, ending on March 14, 1982. Due to delays in the funding of a follow-on contract, the initial ending date was extended with added costs to August 31, 1982.

The original proposal, a joint effort of ten co-principal investigators, (see section II) included efforts in several areas of interest, namely spread-spectrum code design and sync acquisition, burst communications, network synchronization, radar pulse compression designs, communication over "messy" channels, and certain topics in system theory and signal processing. Significant progress has been made in most of these areas, with virtually none of the proposed problems having been found totally intractable. Rather, our major research difficulties have arisen from limited resources, namely time, research assistants, and computer facilities. Improvements in the latter two items have been included in the follow-on grant, DAAG-29-82-K-0142, which commenced September 1, 1982.

This initial contract and the organization which it imposed on the faculty, was one driving force in the formation of a Communication Sciences Institute at USC. Hopefully the CSI structure will

facilitate the administration and direction of future research efforts in communications.

Throughout the duration of this contract, our reporting objective has been to place research results in the open literature where they will be available to all. Accordingly, section III of this final report consists of a listing of papers produced under this contract, along with their abstracts.

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A. SYNCHRONIZATION AND MULTIPLEXING IN DIGITAL COMMUNICATIONS

Comments from R. Gagliardi

In this task several problems were examined in the areas of synchronization, timing, and multiplexing in digital systems. The major effort was in the area of multiplexing multiple, independent data links over a common quadrature channel. The study produced one paper and is the topic of the Ph.D. dissertation of R. Anderson presently under preparation. The primary objective was to determine the degradation effect of sending more than two data streams over a generalized QPSK channel. Several encoding and optimal decoding schemes were considered and performance levels were computed in terms of error probabilities and increased channel capacities.

A study of phase referencing in BPSK systems, using Costas loops augmented by auxiliary gain control loops, was also completed.

****

- R. Gagliardi, and R. Anderson, "M-Link Multiplexing and Demodulation for the Quadrature Channel", Proc. of the National Telecommunications Conference, Houston, Texas, Dec. 1980. (30 copies sent with prior report)

In QPSK signaling two independent data streams are transmitted over a single carrier channel by separately encoding each on to a quadrature component of the carrier. In this paper we investigate the possibility of encoding M independent (non-synchronized and unrelated in data rate) bit streams simultaneously over the same quadrature channel. The multiplexing can be viewed as the generation of a phase

modulated carrier which can phase shift at any instant according to the bit sequences. Decoding can be viewed as separate phase coherent decoding of each bit stream, or equivalently, as a mapping of the quadrature waveforms into M-fold vector estimates of the bit sequences. It is shown that the entire modulation and demodulation can be conveniently viewed in terms of signal vectors in 2-dimensional signal space, where the advantages of the various encoding formats is clearly depicted. Performance results for the case M=3 are presented.

****

- K. Anderson, Synchronous Multiplexing for the Digital Quadrature Channel, Dissertation to be presented to the Electrical Engineering Department, University of Southern California, Fall 1982 (in preparation).

The communication problem we wish to study is that of a digital communication link servicing multiple independent, asynchronous users over a single, common, quadrature channel. A quadrature channel is one using a single carrier that can be either amplitude and/or phase modulated for data transmission. The multiple users communicate over this common channel by having their data bits encoded onto the quadrature carrier. If the data bits were all aligned and synchronized, communication can occur via standard block encoding schemes, such as multiple-level phase shift keying or amplitude shift keying, and performance of such systems is well documented. When the user data is not synchronized, carrier encoding and receiver decoding procedures are no longer obvious, and performance cannot be readily determined from synchronous results.

If only two users were to be accommodated on a quadrature channel, asynchronous communication can be attained using quadrature phase shift keying (QPSK). The two data sources can be orthogonally segmented during transmission and no effect of either source appears in the other decoder. When more than two users are involved in a quadrature channel, they can no longer be orthogonal, and some degree of cross-coupling occurs during mutual decoding. The procedures for encoding and decoding asynchronous users must therefore be re-examined, and subsequent performance levels must be computed.

In this dissertation we will study, in general terms, techniques of encoding n (n>2) independent bit streams simultaneously over the same quadrature channel. In particular, we are interested in the case where each receiver is interested only in deciphering messages from its transmitter pair, and each transmitter source is interested only in communicating messages to its receiver pair. Various types of modulation, or signalling techniques will be presented with the ultimate objective of presenting comprehensive performance capabilities of each technique as well as to study optimal receiver configurations for them. Three critical performance parameters are utilized to assess link performance; bit error rate (BER) performance versus the signal to noise ration, the occupied spectral bandwidth and the statistical channel capacity.

****

– E. Gagliardi, "Coupled AGC-Costas Loops with AM/PM Conversions", IEEE Trans. on Communications, Vol. 28, no. 1, January 1980. (30 copies sent with prior report)

Costas loops are invariably designed in conjunction with an automatic gain control (AGC) loop for stabilizing performance. In such systems an inherent coupling between the AGC and Costas loops develops, complicating the standard phase referencing analysis. This coupling is further emphasized if the gain control amplifier introduces an AM/PM conversion, which causes power variations to enter the Costas loop as phase variations. In this paper the coupling effect between AGC and Costas loops is developed, leading to a pair of joing interconnected dynamical tracking loops. Some degree of solution is attainable by assuming a first order AGC loop, and resorting to quasi-stationary analysis for evaluating the phase referencing generation. Results with and without AM/PM are presented, and illustrate how an improper AGC may in fact degrade the phase referencing from the expected performance.

B. OPTICAL COMMUNICATIONS

In this task problems associated with encoding, decoding, and pointing methods for future generation optical communication systems were studied. Results were obtained in the areas of encoding and decoding of optical PPM, statistical receiver modeling, receiver performance, optical beam pointing and tracking, and possible future applications of laser communications.

****

– G. Prati, and R. Gagliardi, "Block Encoding and Decoding for the Optical PPM Channel", IEEE Trans. on Information Theory, Vol. IT-28, No. 1, January 1982, pp. 100-105. (30 copies sent with prior report)

Pulse position modulation (PPM) is a popular signaling format in pulsed optical communication links. PPM encoding is extended to include block pulse encoding over multiple PPM frames. Maximum likelihood decoding operations associated with this encoding are developed for both shot-noise limited and thermal-noise limited optical receiver models. Both ideal (Poisson) and avalanche photodetectors are considered, and it is shown that optimal block decoders involve combinations of linear and quadratic operations. Error probability bounds are presented, showing the relative improvement in detectability that appears possible by resorting to block encoding over multiple frames.

****

- R. Gagliardi and G. Prati, "On Gaussian Error Probabilities in Optical Receivers", IEEE Trans. on Comunications, Vol. Com-6, Sept. 1980. (30 copies sent with prior report)

The output voltage of an optical receiver is statistically a mixture random variable, composed of the sum of a discrete count variable and a continuous Gaussian thermal noise variable. Based on some computer analyses, it is shown here that threshold crossing probabilities using the mixture density can be reliably approximated by integrations of an equivalent continuous Gaussian density. The conditions for this approximation and an accurate assessment of its error are derived.

****

- R. Gagliardi, "Error Probabilities in Lasercom PPM Systems", Proceedings of the National Telecommunications Conference, IEEE, December 1981, pp. B10.1.1-B10.1.2. (20 copies sent

with prior report)

In laser communication (lasercom) systems, a popular signaling scheme is the use of pulse position modulation (PPM) to transmit digital data. Performance evaluation then depends on the resulting bit error probability, as with any digital link. As the encoding methods used with PPM become more complex, the corresponding error probability formulas likewise become more difficult to evaluate. In this paper we review and list some basic bit error probability equations that can be easily evaluated or computed for estimating expected system performance. At the power levels usually occurring in practice, photoelectron counts will be relatively high ($\geq$ 50) to justify the Gaussian statistics used in the computations.

****

– R. Gagliardi and M. Sheikh, "Pointing Error Statistics in Optical Beam Tracking", IEEE Trans. on Aerospace and Electronic Systems, Vol. AES-16, No. 5, pp. 674-682, September, 1980. (30 copies sent with prior report)

In tracking optical beams from a source, a pointing error signal is derived from photodetecting the field in the receiver focal plane. This error signal is then used in some manner to control a gimballed system that continually points the receiver optics toward the source. When the source field undergoes turbulent transmission, the optical beam is attenuated and scattered, and the field is randomly defocused at the receiver. In this case the pointing error or the tracking system will evolve as a random vector process in time, statistically related to the random scattering, the photodetection process, and the

dynamic of the gimballing system. Such vector processes have probability densities that satisfy well-known differential equations. These equations are derived in terms of accepted scattering models and tracking systems, assuming quadrant-type error detectors are used in the focal plane. Approximate solutions are obtained and analyzed for typical operating conditions, and the manner in which the degree of scattering degrades the entire pointing operation is shown.

****

- R.M. Gagliardi, "Optical Communications for Deep Space Satellite Missions," Proc. of the SPIE, San Diego, California, Aug. 1980. (30 copies sent with prior report)

Some initial considerations are given for an Earth-orbiting relay system using optical data link from deep space and RF links to ground. The advantages of such a system are presented, and some preliminary design concepts and modulation formats are proposed. The tracking and pointing problem is discussed with some indication of capabilities and limitations.

The use of laser beams for satellite communications is now being developed as a viable system alternative. Recently there has been interest in extending these optical systems to deep space missions. Although the clear weather advantages of a terrestrial deep-space link are apparent, the deletorious effect of atmosphere, weather, and turbulence must be taken into account. These effects combine to introduce direct attenuation, possible outage times, and place restrictions on the minimal values of beam widths and pointing

accuracies. A system that retains the optical transmission advantages while avoiding the hazards of weather effects is the employment of an optical relay system. Here a satellite relay, located outside the Earth's atmosphere, maintains an optical receiver for the reception of deep space transmissions. The optical receiver operates in conjunction with an RF terrestrial link for data return to Earth. In this report some preliminary design considerations, performance capabilities, and apparent problem areas are presented for a hypothetical optical deep space-relay system.

C. PROPERTIES OF SEQUENCES WITH SPECIAL RECURSION AND CORRELATION PROPERTIES

****

- S.W. Golomb, "On the Classification of Balanced Binary Sequences of Period 2^n-1", IEEE Trans. on Information Theory, Vol. IT-26, No. 6, Nov. 1980. (50 copies sent with prior report)

Let U be the set of all binary sequences of period $p=2^n-1$ containing $(p+1)/2$ ones and $(p-1)/2$ zeros per period. There is a lattice of interesting subsets of U, the smallest of which is set PN (the maximum-length linear shift register sequences of period p). In between are sets with the run statistics of PN, with the correlation properties of PN, with the "span-n property" (that every nonzero subsequence of length n occurs in each period), and others. Results concerning the interrealtionships of these subsets are nonempty, and conjectures are formulated regarding other intersections of subsets.

for example, it is conjectured that all span-n sequences with the two-level autocorrelation property are in class PN. Some relationships between run properties and correlation properties of binary sequences are also obtained.

****

- U. Cheng, Properties of Sequences, Ph.D. Dissertation, Department of Electrical Engineering, University of Southern California, Los Angeles, CA, December 1981. (1 copy sent with prior report)

The major goal of this research is to develop more properties about sequences. Several interesting topics are discussed, which include: 1) the relations between run distributions and periodic auto-correlations, 2) the auto-correlation propeties of span-n sequences, 3) a new way to search for all the two-level auto-correlation sequences of certain period, 4) the cycles periods distributions of some nonlinear shift registers, and 5) Golomb's sequences.

The formula which relates the periodic auto-correlations and run distributions states that the periodic auto-correlations can be determined from the number of various kinds of suits in the sequence, where suite is the concept defined by the number of runs and the length of the vector which consists of these runs.

The span-n sequences which have two-level auto-correlations have been interpreted from both the high-order auto-correlations and the algebraic-monomorphic function sequences point of view.

By using the results about cyclic difference set, we are able to find

all the two-level auto-correlation sequences of period 255. There are, in total, 64 of them. However, none of them can serve as the counter-example for Golomb's conjectures. Among 80 two-level auto-correlation sequences of period 127, except for 18 PN-sequences, two of them are of the most interest because they satisfy the randomness properties, that is, they are counter-examples for one of Golomb's conjectures.

The cycles periods distributions of the nonlinear shift registers whose feedback functions possess certain kinds of symmetry are very simple. Actually, the periods of these cycles are always the factors of an integer determined by the feedback function. And, usually, this kind of nonlinear shift registers cannot generate a de Bruijn sequence.

A new recursive integer sequence is defined and some statistical data is derived. These data show that this sequence possesses the random nature. Its simplified version, called Golomb's sequence, is studied in detail. The cycle structure of Golomb's sequence is developed and the algorithms to construct some interesting cycles are given.

****

- S.W. Golomb, "Correlation Properties of Periodic and Aperiodic Sequences, and Applications to Multi-User Systems", in New Concepts in Multi-User Communication, J.W. Skwirzynski, ed., Sijthoff & Noordhoff International Publishers, B.V. Alphen aan den Rijn, The Netherlands, 1981, pp. 161-197, (This book contains the complete Proceedings of the 3rd NATO Advanced Study Institute.) (20 copies enclosed with this report)

When two people wish to speak at once, we may ask them to await their turns, or to hold their conversations in separate rooms. These are examples of time division and space division of the available channel. Another strategy is to have them sing a duet, one in the soprano range and the other in the bass. This is frequency division of the channel, and if your ear is equipped with a band-pass filter, you can tune in to one or the other. The problem of code division is to write a duet for two tenors, who will be occupying the same regions in time, space, and frequency, in such a way that a listener can choose to follow one or the other without getting confused. And if you can solve that problem, then we will ask you to try your hand at trios, octets, and the Vienna Boys' Choir. Would it help to have each one of them singing a different language ? I would accept that as an attempt at code division multiple access (CDMA). You could argue that if you understand only one of the languages being used, how could the others, which you don't understand, possibly confuse you ? Well, they can. A flippant response is that we are constantly being confused by the things that we don't understand.

The analytical approach to this type of problem is to recognize that for a very large class of channels, the optimum receiver is a correlation detector, and we would like distinct messages to have mutually low cross-correlation. As you see, I am about to make the transition from polyphonics in the opera house to my real subject, which involves digital signals, usually binary, being typically sent over radio frequency channels, though I reserve the right to mention sonar applications. But before we leave La Scala, or Covent Gardens,

of the fact, I would like to squeeze one more drop from my operative analogy. It is clearly easier to pick up one voice out of two than one out of fifty, all other things, including relative signal power, being equal. We might imagine a composer with the combinatorial virtuosity of a J.S. Bach, or the geometric insight of a W.A. Mozart, writing parts for eight tenors in such a way that if any two of them sing at once, it is relatively easy to separate them. But that is clearly a different problem, and in general easier, than scoring for them in a way that allows all eight to sing at once and remain individually intelligible. So we must distinguish, if we say we have a good set of n signals for CDMA application, whether we expect only two, or three, or all n, to be in use at the same time.

****

— U. Cheng and S.W. Golomb, "Relations Between Run Distributions and Periodic Auto-Correlations", Submitted to IEEE Trans. on Information Theory. (1 preprint enclosed with this report)

General relations between run distributions and periodic auto- correlations are developed. Run distributions are described in terms of entities called suites which are subsequences consisting of consecutive runs. For periodic auto-correlations, only the lengths of the suites and the number of runs in them are important. The occurrences of various n-tuples in a given sequence are not mutually independent. In fact, half of them are already enough to determine the others.

****

– U. Cheng, and S.W. Golomb, "On the Recursion $a_n = a_{n-a_{n-1}}$", Submitted to Information and Control. (1 preprint enclosed with this report)

Properties of the recursion $a_n = a_{n-a_{n-1}}$ are studied. A simple algorithm for the construction of its cycles is given. The cycles for which the maximum term is smaller than the period are of special interest. Examples of such cycles are given. In fact, the period may exceed the largest term of the sequence by an arbitrarily large factor.

– U. Cheng, and S.W. Golomb, "On the Characterization of PN Sequences", Submitted to the IEEE Trans. on Information Theory. (1 preprint enclosed with this report)

D. RESULTS IN COMBINATORIAL ANALYSIS AND NUMBER THEORY APPLICABLE TO RESEARCH IN CODED COMMUNICATIONS

****

– S.W. Golomb, "Iterated Binomial Coefficients", American Math. Monthly, Vol. 87, No. 9, Nov. 1980. (30 copies sent with prior report)

It is traditional in mathematics to explore iteration of operations, and when these are non-commutative and non-associative, there are usually quite interesting properties to be uncovered. Thus, there is certainly nothing bizarre about considering such expressions as c^{b^a}, the result of iterating the exponential operation. Far less common, however, is discussion of the expression $\binom{\binom{c}{b}}{a}$, the result of iterating the "binomial coefficient operation". Yet this expression even has a natural combinatorial interpretation: "the number of subsets of size a which can be formed from the collection of subsets of size b from a

class of size c"; that is, the number of a-tuples and b-tuples in a set of size c. Perhaps it is because the notation is ungainly, especially when we try to consider further iterates, such as $\binom{\binom{d}{c}}{\binom{b}{a}}$, that this subject has been neglected. (The older notation was no better: $C_a^{C_b^c}$, and $C_a^{C_b C_c^d}$, etc!)

Let us therefore establish a notation more amenable to typesetting. Define $(a_1;a_2;\ldots;a_k)$ inductively by $(a_1) = a_1$, $(a_1;a_2) = \binom{a_1}{a_2}$, and $(a_1;a_2;\ldots;a_{k-1};a_k) = ((a_1;a_2;\ldots;a_{k-1});a_k)$. Thus $(a_1;a_2;a_3) = \binom{\binom{a_1}{a_2}}{a_3}$. For $k \leq 3$, we will frequently continue to use the "vertical notation" as well as the "horizontal notation", because of its greater familiarity and visual impact.

In this paper, we will explore identities, inequalities, equations, divisibility properties, extremal problems, and reduction formulas involving iterated binomial coefficients. This is not intended as a definitive treatment, but as an initial exploration into rich new territory.

****

– P. Erdos, A.L. Rubin and d. Taylor, "Choosability in Graphs", published in Proceedings of the Humboldt State University Conference on Graph Theory, Combinatorics and Computing, 1980. (20 copies enclosed with this report)

A graph is 2-choosable iff each connected component is 2-choosable, so we restrict our attention to connected graphs. To start the investigation of which graphs are 2-choosable, consider a node of valance 1. We can always choose one of its two letters after deciding

which letter to choose from the one node adjacent. The obvious thing to do is prune away nodes of valence 1, successively until we reach the core, which has no nodes of valance.

Among the theorems proved is: A graph is 2-choosable if, and only if, the core of G belongs to

$$T = \{K_1, C_{2m+2}, \theta_{2,2,2m} : m \geq 1\}$$

****

- S.W. Golomb, "The Evidence for Fortune's Conjecture", Mathematics Magizine, Vol. 54, September 1981, pp. 209-210. (20 copies sent with prior report)

Euclid's proof that there are infinitely many primes is based on the observation that if $b_n = p_n + 1$ is not itself prime (where $P_n = p_1 p_2 \cdots p_n$ is the product of the first n primes), it must still contain a prime factor larger than p_n.

E. MATHEMATICAL MODELS OF BASIC PHYSICAL PHENOMENA

****

- S.W. Golomb, "Rubik's Cube and a Model of Quark Confinement", American Journal on Physics, Vol. 49, No. 11, November 1981, pp. 1038-1041. (20 copies sent with prior report)

Designating a $+120^{\circ}$ rotation ("twist") of a corner cell of Rubik's cube™ (a popular geometric puzzle) as a (mathematical) quark, and a -120° rotation of a corner cell as a (mathematical) antiquark, the same restrictions that confine physical quarks are observed to hold,

viz. isolated quarks cannot arise, and in general, combinations of quarks and antiquarks can only occur if the excess of one type over the other is a multiple of three.

F. ADAPTIVE NOTCH FILTERING FOR SPECTRAL LINE ESTIMATIONS

– D.V.B. Rao, and S.Y. Kung, "Adaptive Notch Filtering for the Retrieval of Sinusoidal Signals in Colored Noise", to appear in IEEE Trans. on ASSP, 1982. (20 copies enclosed with this report)

A notch filtering technique is developed for estimating the frequencies of sinusoidal signals in additive, uncorrelated noise, colored or white. The technique may be regarded as a blend of the time and frequency domain approaches. First, it is shown that a frequency domain analysis leads naturally to the adoption of the notch filter for unbiased estimates of the frequencies. Then an approximation in the time domain analysis leads to a constrained autoregressive moving average model which results in a simplified parameterization of the filter. This model is useful in establishing its connection to existing popular methods: autoregressive model based and Pisarenko's harmonic decomposition methods. For adaptive estimation of the parameters a stochastic Gauss-Newton method is developed, and the related convergence issues are examined. For the implementation of the filter, in addition to direct forms, efficient Cascade and Parallel forms are also examined. More significantly, the method possesses the frequency decoupling property typical of

frequency domain methods which allows the problem to be partitioned into smaller subproblems for parallel processing. The simulation results presented support and substantiate the method and analysis.

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- S.Y. Kung, and D.V.B. Rao, "Analysis and Implementation of the Adaptive Notch Filter for Frequency Estimation", Proceedings of the International Conference on Acoustics, Speech, and Signal Processing, London, May 1982. (20 copies enclosed with this report)

This paper enhances some theoretical and implementation aspects of a constrained autoregressive moving average model, the notch filter model developed in [1] for the estimation of sinusoidal signals in additive, uncorrelated noise, colored or white. This model is shown to approximate the actual signal plus noise model. In addition, the parameter estimates obtained by minimization of the output power of the notch filter approximate the maximum likelihood estimate of the model parameters. The relationship of the notch filtering approach to the existing autoregressive and Pisarenko methods is established. Next, a scheme to combine fast convergence and unbiased estimation is suggested. Lastly, certain implementation aspects of the filter are considered and the method is shown to be amenable to parallel processing.

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- S.Y. Kung, and D.V.B. Rao, "An Unbiased Adaptive Method for Retrieval of Sinusoidal Signals in Colored Noise", Proceedings of the 20th IEEE Conference on Decision and Control, pp. 801-807, December 1981. (20 copies sent with prior report)

The problem of retrieving narrowband or sinusoidal signals in additive noise, colored or white, is considered in this paper. A frequency-domain analysis leads to a notch filter estimator producing unbiased estimates of the sinusoidal frequencies. The notch filter lends itself naturally to a frequency decoupled realization i.e. cascaded form realization. This has desirable numerical consequences which is essential for resolving closely spaced spectral lines. The method also features an adjustable debiasing parameter whose proper adjustment results in a decent rate of convergence to highly accurate estimates. Based on some frequency-tracking simulations, the method also appears to possess good tracking capability.

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– S.Y. Kung and D.V.B. Rao, "Adaptive Notch Filtering for Spectral Line Enhancement", ASSP '81. (20 copies enclosed with this report)

This paper presents a new perspective to the problem of recursive spectral line enhancement, namely that of retrieving narrow-band or sinusoidal signals in additive noise, colored or white. Through a frequency-domain analysis, a new adaptive method based on a special notch filter structure is adopted. Theoretically, unlike most existing methods, the new method is capable of producing unbiased estimates of the sinusoidal frequencies; practically, the method also possesses some strong numerical features: Due to parametric sensitivity, a cascade structure has to be used in lieu of a canonical structure in order to resolve closely spaced spectral lines. Due to the special frequency characteristics of the notch filter, a modified

gradient method is proposed to ensure a robust adaptive adjustment of the filter coefficients. Finally, the method features an adjustable debiasing parameter whose proper adjustment results in a highly accurate estimate at a very decent convergence rate. Based on numerous simulations conducted, the method appears to exhibit high accuracy, high resolution as well as excellent tracking capability.

G. STOCHASTIC REALIZATION AND HIGH-RESOLUTION SPECTRAL ESTIMATION

- S.Y. Kung, and Y.B. Hu, "Improved Pisarenko's Sinusoidal Spectrum Estimate via SVD Subspace approximation methods", Proceedings 21st CDC, Orlando, Florida, Dec. 8-9, 1982. (1 preprint enclosed with this report)

This paper presents two numerically stable Pisarenko type spectrum estimators based on a subspace approximation approach. A sinusoidal signal plus noise model is assumed. By using the singular value decomposition, the covariance matrix is decomposed into a signal subspace which represents the signal component; and a noise subspace which represents the noise contributions. The first method makes use of a signal subspace structure which characterizes the signal covariance matrix by a linear system triple $(A,\underline{b},\underline{c})$. Then the frequencies of the signal sinusoids are solved as the eigenvalues of the A matrix. The second method utilizes a Toeplitz structure of the noise subspace. Then a subspace approximation procedure is taken to find an estimate of this noise subspace. The frequency estimates are then solved as the roots of the defining sequence of this Toeplitz noise subspace matrix. Simulation results are furnished to illustrate the advantages of these proposed new methods.

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- S.Y. Kung, "Partial Realizations: Existence, Uniqueness and Minimality", Proceedings of International Symposium on Circuits and Systems, Rome, May 1982. (20 reprints enclosed with this report)

This paper develops some basic rank properties on Hankel matrices which lead to a simple solution to the fundamental questions of the existence, uniqueness, and minimality of partial realization. This result plays a role in systems parametrization which has several applications as illustrated in the example given.

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- S.Y. Kung, "New Unbiased Methods for Narrowband Spectral Estimation", IFAC on Theory and Application of Digital Control, New Delhi, India, pp. 1-6, January 5-7, 1982. (20 reprints enclosed with this report)

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- S.Y. Kung, "A Toeplitz Approximation Method and Some Applications", International Symposium on Mathematical Theory of Networks and Systems, Santa Monica, CA, pp. 262-266, Aug. 5-9, 1981. (20 copies sent with prior report)

A narrowband/sinusoidal signal retrieval problem is formulated in terms of its Toeplitz autocovariance matrix and a Toeplitz approximation method based on singular value decomposition is proposed.

H. MODEL REDUCTION VIA SINGULAR VALUE DECOMPOSITION

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- Y.V. Genin and S.Y. Kung, "A Two-Variable Approach to the Model Reduction Problem with Hankel Norm Criterion", IEEE Trans. on Circuits and Systems, Vol. CAS-26, No. 9, pp. 912-924, Sept. 1981. (20 copies sent with prior report)

A two-variable approach to the model reduction problem with Hankel norm criterion is discussed. The problem is proved to be reducible to obtaining a two-variable all-pass rational function, interpolating a set of parametric values at specified points inside the unit circle. A polynomial formulation and the properties of the optimal Hankel norm approximations are then shown to result directly from the general form of the solution of the interpolation problem considered.

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- S.Y. Kung, and D.W. Lin, "Optimal Hankel Norm Model Reductions: Multivariable Systems", IEEE Trans. on Automatic Control, Vol. AC-26, No. 4, pp. 832-852, August 1981. (20 copies sent with prior report)

This paper represents a first attempt to derive a closed-form (Hankel-norm) optimal solution for multivariable system reduction problems. The basic idea is to extend the scalar case approach to deal with the multivariable system. The major contribution lies in the development of a minimal degree approximation (MDA) theorem and a computation algorithm. The main theorem describes a closed-form formulation for the optimal optimal approximants, with the optimality verified by a complete error analysis. In deriving the main theorem,

some useful singular value/vector properties associated with block-Hankel matrices are explored and a key extension theorem is also developed. Imbedded in the polynomial-theoretic derivation of the extension theorem is an efficient approximation algorithm. This algorithm consists of three steps: (i) compute the minimal basis solution of a polynomial matrix equation; (ii) solve an algebraic Riccati equation; and (iii) find the partial fraction expansion of a rational matrix.

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- S.Y. Kung, and D.W. Lin, "Recent Progress in Linear System Model-Reduction via Hankel Matrix Approximation", invited lecture for State-of-the-Art Review of Systems Approximation, European Conference on Circuit Theory and Design (ECCTD) '81, The Hague, The Netherlands, August 1981. (20 copies included with this report)

This paper presents a brief review of several major approaches to linear system model reduction problems. Emphasis is placed upon two classes of Hankel approximation methods. Using a singular value decompositions on the system Hankel matrix, the singular values/vectors are categorized into principal-component and perturbational-component sets. The first kind of Hankel approximation method adopts an adjustment of the Hankel matrix, with the adjustment derived from perturbational singular values/vectors. Both discrete-time and continuous time cases are considered. Simulation results and comparisons are documented. Finally, the paper briefly reviews Hankel approximation methods for multivariable systems; and it further suggests a new scheme for solving frequency-weighted approximation problems.

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- D.W. Lin and S.Y. Kung, "Optimal Hankel-Norm Approximation of Continuous-Time Linear Systems", Circuit, System, & Signal Process, Vol. 1, No. 3-4, Birkhaeuser, Inc., Boston. (1 preprint included with this report)

A problem on optimal approximation of continuous-time linear systems is studied. The performance measure (error) is chosen to be the spectral norm of the difference between the Hankel operators associated with the original system and the approximant. It is shown that the Hankel operators associated with continuous-time systems and the Hankel matrices associated with discrete-time systems are related by an interesting correspondence property via bilinear transforms. This fact is then used to derive the continuous-time results (theory and algorithms) from the established discrete-time ones. Some simple examples are presented.

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- S.Y. Kung, and D.W. Lin, "A State-Space Formulation for Optimal Hankel-Norm Approximations", to appear in IEEE Trans. on Automatic Control, Vol. AC-26, No. 4, pp. 942-946, August 1981. (20 copies sent with prior report)

The optimal Hankel-norm approximation problem studied in [1] is reformulated in a state-space setting. The crucial Extension Theorem is re-established in this framework. The minimal degree optimal approximation is then derived in terms of state-space parameters.

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- S.Y. Kung, "Optimal Hankel-Norm Model Reductions - Scalar Systems", To appear on IEEE Trans.on Automatic Control. (1

preprint enclosed with this report)

This paper deals with the optimal Hankel-norm model reductions via a polynomial approach. The major contributions include (i) a simple generalized eigenvalue problem formulation yielding a closed-form solution for the minimal-norm-approximation problems, and (ii) a fast MFD (matrix-fraction-description) algorithm, based on an adjoint system matrix, for the minimal-degree-approximation problems. Significantly, the same approach can also be successfully extended to continuous-time as well as multi-variable systems.

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- S.Y. Kung and D.W. Lin, "Optimal Hankel-norm Reductions: Multivariable Systems", Proc. of the 1980 Conference on Decision and Control, pp. 187-194, New Mexico, December 1980. (30 copies sent with prior report)

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- S.Y. Kung, "A New Low-Order Approximation Algorithm via Singular Value Decomposition", Submitted to the (IEEE Trans. on Automatic Control. (1 preprint enclosed with this report)

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- S.Y. Kung, "New Fast Algorithms for Optimal Model Reductions", Proc. of the 1980 JACC, San Francisco, CA, Aug. 1980. (1 copy sent with prior report)

I. NETWORK SYNCHRONIZATION

- W.C. Haymann, and W.C. Lindsey, "Network Synchronization Techniques," NATO Advanced Study Institute, Norwich, England, August 4-6, 1980. (20 reprints enclosed with this report)

The purpose of this paper is to introduce the reader to some recent network synchronization results. First several network synchronization techniques are summarized. This is followed by presenting a unified mathematical model which characterizes the statistical behavior of a broad class of network synchronization techniques, e.g., plesiochronous, hierarchial master slave and mutually synchronized networks with and without delay compensation. Results on the stability of these networks as well as the steady state behavior are presented. For example, the steady state network frequency and time differences between nodes under a no noise condition are evaluated. Finally, the effects of clock drift are given along with a growth algorithm for the initial construction of a synchronous network.

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– F. Ghazvinian, and W.C. Lindsey, "Dissemination of Time in a Digital Communication Network," National Radio Science Meeting, January 12–16, 1981, Boulder, Colorado. (Abstract only.) (1 copy sent with prior report)

In recent years the importance of digital communications has become more apparent and a variety of digital communica- tion networks have been developed. One of the major obstacles in developing an efficient network is associated with the task of synchronization of the frequency and phase of all clocks in the network. This paper investigates a method of clock synchronization in mutually connected communication networks. In this technique, delay lines are introduced at each node to compensate for the transmission delays encountered by

the timing signals. It is shown that this method can be extended to include the synchronization of networks with moving terminals which are subject to such factors as the change in transmission delay and the frequency shift by doppler effect. The performance criterion in a synchronized network is based on the time difference between the clocks in the network. These time error processes are random in nature and depend on frequency drift and phase noise of the oscillators. In this paper a general matrix expression is derived for the N-th structure function of time error process. For certain topologies of interest, these structure functions are computed for mutually synchronized networks and their results are compared to the case where there are no couplings between the clocks.

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- W.C. Hagmann and W.C. Lindsey, "Some Results on Time and Frequency Transfer in Mutually Synchronized Networks," National Radio Science Meeting, January 12-16, 1981, Boulder, Colorado. (Abstract only) (1 copy sent with prior report)

A general mathematical model describing time and frequency distribution networks is presented. Special attention will be given to mutual synchronization. Various functional models shall be introduced. A linearized mathematical model and its applicability will be discussed. Sufficient conditions for network stability will be given and approximate pole locations will be presented for a special "equal delay" network. The steady state behavior, i.e., the steady state network frequency and the steady state nodal time errors will be developed. The influence of clock drift on these time errors

will be investigated and an example given. A special network growth algorithm is presented which minimizes the disturbances to the synchronous network as it grows.

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– W.C. Lindsey, F. Ghazvinian, and W.C. Hagmann, "Time and Frequency Transfer in Data Communication Networks", International Symposium on Information Theory, February 9–12, 1981, Santa Monica, California (Abstract Only). (1 copy sent with prior report)

One of the major problems in developing an efficient digital communication network is associated with the task of the network. Different methods or distributing time and frequency are discussed and a general mathematical model describing all these techniques is developed. Special attention is given to mutual synchronization and functional models are introduced for this method.

Performance measures for time and frequency distribution networks are discussed. The influences of frequency drift and phase noise process of the clocks on the time error processes are investigated. A comparison is made between mutually synchronized and plesiochronous networks. Finally, a special network growth algorithm is presented which minimized network disturbances due to topological changes in the network structure.

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– W. Hagmann, F. Ghazvinian, and W.C. Lindsey, "Synchronization Techniques for Mobile User Satellite Systems", Proceedings of the International Communications Conference, IEEE, June 1981, pp. 59.4.1–59.4.5. (20 copies

sent with prior report)

It is shown in this paper how the structures of a class of closed loop ranging and synchronization systems follow readily from a basic open loop time dissemination and ranging technique. The channel delay is tracked in a closed loop fashion and this estimate is used to precorrect the data transmission. This dynamic precorrection reduces the influence of channel dynamics and makes the system attractive for satellite systems with mobile users.

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— W.C. Lindsey, F. Ghazvinian, and W.C. Hagmann, "Effects of Clock Phase Instabilities on the Performance of Synchronous Networks", Submitted for publication to NTC. (1 preprint sent with prior report)

This paper investigates the effects of phase instabilities on the performance of a synchronous digital communication network.

The performance of the network is characterized in terms of the n-th increment of the time processes observed at the nodes and the time error generated between the network nodes and their associated structure function.

A mathematical model describing the operation of the network is developed. This model is then used to show how the clock phase instabilities influence the synchronization accuracy in plesiochronous, master-slave and mutually synchronized networks of clocks. It is shown that synchronous networks exhibit a smaller time error variance within the network than plesiochronous networks. It is

also shown that the network time process in a mutually synchronized network is less influenced by the oscillator phase noise than the one in a master-slave network.

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- W.C. Lindsey, W.C. Hagmann, and F. Ghazvinian, "Network Synchronization Techniques: An Overview", Submitted for publication to NTC. Also published in ntz Archiv Bd. 4 (1982), pp. 163-168. (20 copies enclosed with this report)

The paper gives an overview over various network synchronization techniques which have been proposed in the literature. It is shown how they can be classified in an easy and straightforward way enabling a fair comparison between the different techniques. Generic advantages and disadvantages of the basic techniques, plesiochronous, master-slave and mutual, are discussed, and an extensive reference list is given.

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- W.C. Lindsey, F. Ghazvinian and W.C. Hagmann, "Phase Noise Effects on Synchronous Network Performance", Proceedings of the National Telecommunications Conference, Institute of Electrical and Electronics Engineers, December 1981, pp. F1.3.1-F1.3.5. (20 copies sent with prior report).

This paper investigates the effects of phase instabilities on the performance of a synchronous digital communication network. The performance of the network is characterized in terms of the n-th increment of the time error process generated between network nodes and its associated structure function. A mathematical model describing the operation of the network is developed. This model is

then used to calculate and compare the structural moments of the time error processes for networks employing plesiochronous, master-slave and mutual synchronization techniques.

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- W.C. Lindsey and H.J. Choi, "Mutual Synchronization of Two Oscillators", National Telecommunications Conference Record, Galveston, TX, 1982 (to appear). (1 preprint enclosed with this report)

In this paper, various approaches for the mutual synchronization of two geographically separated oscillators are presented. Mathematical models of these systems are proposed and network performance measures are defined. It is shown that performance can be improved by different methods of implementation at the expense of network complexity.

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- K. Dessouky and W.C. Lindsey, "Statistical Characterization of a System of Two Mutually Synchronized Oscillators", National Telecommunications Conference Record, Galveston, TX, 1982 (to appear). (1 preprint enclosed with this report)

This paper presents a theory for a system of two mutually synchronized phase-locked oscillators. The theory is based on the treatment of sinusoidal phase-locked loops operating in the nonlinear regime. Three key phase increment processes are defined, their physical meaning explained and their probability density function derived. The effects of transmission delays and frequency instabilities in the system are studied through their effects on the densities of these

increments.

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- W.C. Lindsey and C.Y. Yoon, "Phase Locked Loop Performance in the Presence of CW Interference and Additive Noise", Accepted for publication in IEEE Trans. on Communications, October 1982. (not yet available)

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- F. Ghazvinian, Synchronization in Digital Communication Networks, PhD dissertation, Dept. of Electrical Engineering, University of Southern California, Los Angeles, CA, August 1981. (1 copy sent with prior report)

Synchronization in digital communication networks, referred to as network synchronization, is basically the distribution of frequency and time to all the nodes in the network.

In the past two decades, the problem of network synchronization has been studied extensively and many techniques have been proposed for achieving synchronization. These techniques can be divided into several different categories depending on the nature of the controlling signals used in obtaining synchronization. The basic operating principle of these synchronization methods and their inherent advantages and disadvantages are discussed in this thesis.

The major consideration in the design of a synchronous network is based on the ease of implementation of the network. In this thesis the functional model of a synchronous network is described. The basic implementation of a two-nodal network with and without delay compensation is presented and, for the case of delay compensated

networks, a delay measurement technique is introduced and its operation is described.

To analyze the behavior of synchronous networks, a unified mathematical model of synchronous networks is developed which is capable of describing the operation of all synchronization techniques. A set of performance measures are defined in order to evaluate the behavior of synchronous networks. Then using the mathematical model of the network, the following performance measures are calculated for several networks with different synchronization techniques and the results are compared with each other.

1. The concepts of stability is defined and sufficient conditions for stable operation of synchronous networks are presented.

2. The steady state network frequency and the steady state time distribution between the nodes of the network are evaluated and the significance of delay compensation techniques is pointed out.

3. The sensitivity of the network to structural changes in its topology is discussed and some techniques are introduced to reduce the perturbation in the network due to addition or deletion of a node to or from the network.

4. The effects of phase noise of the clocks on the time error process between the nodes in the network are evaluated for different networks and it is shown that mutual synchronization has the property of reducing the effect of phase noise.

Finally, problems of synchronization of nonstationary networks are pointed out and some measures are introduced to overcome these difficulties.

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– K. Dessouky, Nonlinear Theory of Mutually Synchronized Oscillators, Ph.D. Dissertation, Department of Electrical Engineering, University of Southern California, November 1982. (Not yet available)

In this thesis, a theory is developed for a system of mutually synchronized oscillators. The system discussed employs phase-locked oscillators with sinusoidal phase detector characteristics. The objective is to characterize the steady state behavior of the system when it operates nonlinearly in the presence of noise. As a result, no attempt is made to approximate or linearize the phase detector characteristics. Instead, the results of the theory of stochastic differential equations are used to obtain the desired statistical characterization of the system.

A mathematical model for the mutual synchronization system is first presented. To obtain explicit results with the nonlinear differential equations evolved, a system of two nodes is considered. Three key phase increment processes are defined and their physical meaning explained. These increment processes describe the phase error in the system, the stability of the time scales at each node, and the time interval error of the system. Through the increment processes, applying the useful tools of non-linear phase-locked loop analysis to mutual synchronization becomes possible.

The core of the thesis contains the development of the stochastic differential equations describing the increment processes, and the derivation of their probability density functions. The synchronization system is affected by noise, transmission path delays,

delay compensation, and oscillator frequency instabilities. The effects they have on the system are studied through their effects on the probability density functions of the different increment processes. The effects of loop gain assymetrics on the phase error in the system are also investigated.

After presenting the density functions of the increment processes obtained by nonlinear analysis, very useful Gaussian approximations for these densities are developed and discussed. To complete the study of the nonlinear behavior of the synchronized system, the phenomenon of cycle slipping, which occurs between and at each of the nodes, is analyzed.

J. APPLICATIONS OF NUMBER THEORETIC TRANSFORMS

- I.S. Reed, H.M. Shao, T.K. Truong, "Fast Polynomal Transform and its Implementation by Computer", IEE Proc., Vol. 128, Pt. E., No. 1, March 1981, pp. 50-60. (30 copies sent with prior report)

Recently a new algorithm was developed to compute two-dimensional cyclic convolution by what is called the FPT (fast polynomial transform) algorithm. In this paper this new algorithm is further studied and implemented on a general purpose computer. Methods to cope with finite core memory limitations are presented and actual computational speed performances are listed.

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- N. Glover, I.S. Reed, T.K. Truong and J.P. Huang, "Methods to Reduce the Table Look-Up Requirements for Finding Logs or Antilogs of Elements in a Galois Field", submitted to IEE

Proceedings, Part F. (1 preprint enclosed with this report)

Let GF(q) be a finite field, where $q=p^m$ and p is prime. Polynomial multiplications in GF(q) required to encode and decode BCH and Reed-Solomon (RS) codes are performed often using log and antilog tables of p^n-1 non-zero field elements. It is shown in this paper that for $q=p^{2n}$ and p^n+1 a prime, the log and the antilog of a field element can be found with two smaller tables of p^n+1 and p^n-1 elements, respectively. The method is based on a use of the Chinese Remainder theorem. This technique results in a significant reduction in the memory requirements of the problem. It is shown more generally that for $q-1=p_1 p_2 \cdots p_k = m_1 m_2 \cdots m_k$, where $m_i=p_i$ for $1 \leq i \leq k$, tables of m_1 elements, m_2 elements,...,m_k elements also can be used to find logs and antilogs over GF(q). In the latter method, further reductions in the memory requirements are achieved, however, at the possible expense of a greater number of operations.

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— I.S. Reed, T.K. Truong, "A New Algorithm for Computing Primitive Elements in $GF(q^2)$", submitted to IEEE Trans. Information Theory. (1 preprint enclosed with this report)

A new method is developed to find primitive elements in the Galois field of q^2 elements $GF(q^2)$, where q is a Mersenne prime. Such primitive elements are needed to implement transforms over $GF(q^2)$.

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- I.S. Reed, T.K. Truong, C.-S. Yeh, H. M. Shao, "An Improved FFT Algorithm for Computing Two-Dimensional Cyclic Convolutions", submitted to IEEE Trans. Acoustics, Speech, and Signal Processing. (1 preprint enclosed with this report)

In this paper, an improved fat polynomial transform (FPT) is developed for computing 2-D cyclic convolutions. In this new procedure the excess-complex multiplications for computing the required polynomial products are eliminated by incorporating them into the FPT computation. Also new algorithms are derived for computing the modulus reductions and reconstruction by the Chinese remainder theorem. It is shown that the latter algorithms have a structure similar to an FFT-type flow-structure. These algorithms reduce the number of additions and shifts needed previously. With these new methods the FPT can be computed with a more systematic structure.

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- T.K. Truong, I.S. Reed, C.-S. Yeh, "Parallel Architectures for Computing Cyclic Convolutions", submitted to IEE Proceedings, Part E. (1 preprint enclosed with this report) (This paper is the same as the one that follows.)

In this paper, two parallel architectural structures are developed to compute one-dimensional cyclic convolutions. The first structure is based on the Chinese remainder theorem and Kung's pipelined linear array in [6,7]. The second structure is a direct mapping from the mathematical definition of a cyclic convolution to an architectural design. To compute a d-point cyclic convolution the first structure needs d/2 inner product cells, while the second structure and Kung's linear array in [6] require d cells. However, to compute a cyclic

convolution, the second structure requires less time than both the first structure and Kung's linear array. Another application of the second structure is to multiply a Toeplitz matrix by a vector. A table is listed to compare these two structures and Kung's linear array in [8]. Both structures are simple and regular, and therefore suitable for VLSI implementation.

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- T.K. Truong, I.S. Reed, C.-S. Yeh, "A Parallel Architecture for Computing Cyclic Convolutions", accepted for publication in TENCON '82, Hong Kong. (1 preprint enclosed with this report)

In this paper, a parallel-pipeline, radix-2 architecture is proposed to implement the fat polynomial transform (FPT). It is shown that such a structure can be used to efficiently compute a two-dimensional convolution of $d_1 x d_2$ complex number points, where $d_1=2^{m-r+1}$ and $d_2=2^m$ for $1 \leq r \leq m$.

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- T.K. Truong, I.S. Reed, C.-S. Yeh, "The VLSI Architecture for a FIR Digital Filter Using Complex Number-Theoretic Transforms", submitted to IEEE Trans. Acoustics, Speech and Signal Processing. (1 preprint enclosed with this report)

In this paper a parallel pipeline architecture is developed to compute the linear convolution of two sequences of arbitrarily long lengths with a complex number-theoretic transform (CNT). In particular a pipeline structure similar to Kung's linear array is designed to compute a 248-point CNT. This CNT requires only additions and bit

rotations. This CNT is used in conjunction with a generalized overlap-save technique to compute a linear convolution of two complex sequences of arbitrarily long lengths. A parallel architecture is developed to realize this generalized overlap-save scheme with one CNT and several inverse CNT of 248 points. Finally, it is shown that the generalized overlap-save method with complexc number-theoretic transforms solves the conflict between long transform lengths and a wide dynamic range of the number-theoretic transform. This architecture is regular, simple, and expandable, and therefore naturally suitable for VLSI implementation.

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- T.K. Truong, I.S. Reed, C.-S. Yeh, H.M. Shao, "A Parallel VLSI Architecture for a Digital Filter of Arbitrary Length Using Fermat Number Transforms", accepted for publication in IEEE International Conference on Circuits and Computers, 1982, New York. (1 preprint enclosed with this report)

In this paper a parallel architecture is developed to compute the linear convolution of two sequences of arbitrary lengths using the Fermat number transform (FNT). In particular a pipeline structure is designed to compute a 128-point FNT. In this FNT, only additions and bit rotations are required. A standard barrel shifter circuit is modified so that it performs the required bit rotation operation.

The overlap-save method is generalized for the FNT to compute a linear convolution of arbitrary length. A parallel architecture is developed to realize this type of overlap-save method using one FNT and several inverse FNT's of 128 points. The generalized overlap-save method

alleviates the usual dynamic range limitation in FNT's of long transform lengths. Its architecture is regular, simple, and expandable, and therefore naturally suitable for VLSI implementation.

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- T.K. Truong, I.S. Reed, R. Lipes, A. Rubin, S. Butman, "Digital SAR Processing Using a Fast Polynomial Transform", submitted to IEEE Trans. Acoustics, Speech and Signal Processing. (1 preprint enclosed with this report)

In this paper, a new digital processing algorithms is developed for producing images from SEASAT Synthetic Aperture Radar (SAR) data. Such SEASAT operates in the stripmapping mode. This algorithm applies the fast polynomial transform (FPT) for computing the two-dimensional cyclic correlation of the raw echo data with the impulse response of a point target. This two-dimensional correlation algorithm solves the range migration problem. It is demonstrated that this SAR processing technique is readily implemented on a general purpose computer. Actual results of SEASAT SAR imagery are given in this paper.

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- T.K. Truong, I.S. Reed, I.-S. Hsu, K. Wang, C.-S. Yeh, "The VLSI Design of a Reed-Solomon Encoder Using Berlekamp's Bit-Serial Multiplier Algorithm", submitted to IEEE Trans. Computers. (1 preprint enclosed with this report)

Berlekamp has developed for the California Institute of Technology Jet Propulsion Laboratory (JPL) a bit-serial multiplication algorithm for the encoding of Reed-Solomon (RS) codes, using a dual basis over a Galois field. The conventional RS-encoder for long codes often

requires look-up tables to perform the multiplication of two field elements. Berlekamp's algorithm requires only shifting and Exclusive-Or operations. It is shown in this paper that the new dual-basis (255,223) RS-encoder can be realized readily on a single VLSI chip with NMOS technology.

K. FRAME SYNCHRONIZATION

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- R.A. Scholtz, "Frame Synchronization Techniques", IEEE Trans. on Communications, pp. 1204-1213, Aug. 1980. (30 copies sent with prior report)

A basic theory of frame synchronization for a single-channel digital communication system is presented, along with extensive references to the literature. The design of frame markers is discussed and comparisons are drawn with more exotic techniques such as comma-free coding.

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- R.A. Scholtz, "Frame Synchronization Concepts", National Radio Science Meeting, Boulder, Colorado, January 12-16, 1981. (Abstract only, same as above.) (1 copy sent with prior report)

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- V.K.W. Wei, and R.A. Scholtz, "On the Characterization of Statistically Synchronizable Codes", IEEE Trans. on Information Theory, Nov. 1980. (30 copies sent with prior report)

The class of all fixed-length statistically synchronizable codes may

be completely characterized in several ways. A simple condition for determining statistical synchronizability is demonstrated.

L. SPREAD SPECTRUM SIGNAL DESIGN

- Olsen, J.D., Scholtz, R.A., and Welch, L.R., "Bent-Function Sequences", accepted for publication in IEEE Trans. on Information Theory, December 1982. (1 revised copy enclosed with this report)

In this paper we construct a new family of nonlinear binary signal sets which achieve Welch's lower bound on simultaneous cross-correlation and autocorrelation magnitudes.

Given a parameter, n with $n=0 \pmod 4$ the period of the sequences is 2^n-1, the number of sequences in the set is $2^{n/2}$ and the cross/auto correlation function has three values with magnitudes $\leq 2^{n/2}+1$. The equivalent linear span of the codes is upper bounded by $\sum_{i=0}^{n/4}\binom{n}{i}$.

These new signal sets have the same size and correlation properties as the small set of Kasami codes, but they have important advantages for use in spread spectrum multiple access communication systems. First the sequences are "balanced" which represents only a slight advantage. Second, the sequence generators are easy to randomly initialize into any assigned code and hence can be rapidly "hopped" from sequence to sequence for code division multiple access operation. Most importantly, the codes are nonlinear in that the order of the linear difference equation satisfied by the sequence can be orders of magnitude larger than the number of memory elements in the generator that produced it. This high equivalent linear span assures that the

code sequence cannot be readily analyzed by a sophisticated enemy and then used to neutralize the advantages of the spread spectrum processing.

- R.A. Scholtz, "Optimal CDMA Codes", National Telecommunications Conf. Record, Washington, D.C., November 1979, pp. 54.2.1-4. (30 reprints sent with prior report)

This paper surveys several known sequence sets which may be used as pread spectrum codes in code-division multiple-access communication systems. All of the designs basically achieve Welch's lower bound on the maximum value of periodic cross-correlation between signals and are optimal in this sense.

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- Scholtz, R.A., Kumar, P.V., and Welch, L.R., "A Generalization of Bent Functions", 1982 International Symposium on Information Theory, Les Arcs, France. (abstract only) (1 copy sent with prior report)

In this paper, Rothaus' definition of a bent function is extended to include a much larger class of functions as follows: Let J_q^k denote the set of k-tuples with elements drawn from the set of integers mod q, and let w be a q root of unit for arbitrary integral q. Then, a function f(x) from J_q^n to J_q^1 is defined to be bent if the Fourier coefficients of $w^{f(x)}$ all have unit magnitude. A large class of such bent functions is exhibited and their properties examined.

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- Kumar, P.V., and Scholtz, R.A., "Bounds on the Linear Span of Bent Sequences", submitted to the IEEE Transactions on

Information Theory. (1 preprint sent with prior report)

Recently, Olsen, Scholtz and Welch presented families of binary sequences called bent-function sequences which are generated through nonlinear operations on m-sequences. These families of sequences possess asympto- tically optimum correlation properties and large equivalent linear span (ELS). In this paper, upper and lower bounds to the ELS of bent-function sequences are derived. The upper bound improves upon Key's upper bound and the lower bound obtained through construction, exceeds $\binom{n/2}{n/4} 2^{n/4}$ where n is the length of the shift register generating the m-sequence. An interesting general result contained in the derivation is the exhibition of a class of nonlinear sequences having large ELS.

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– P.V. Kumar, R.A. Scholtz, and L.R. Welch, "Generalized Bent Functions and Their Properties", submitted to the Journal on Combinatorial Theory. (1 preprint enclosed with this report)

Let J denote the set of m-tuples over the integers modulo q and set $i = \sqrt{-1}$, $w = e^{i\frac{2\pi}{q}}$. As an extension of Rothaus' notion of a bent function, a function f, $f : J_q^m \rightarrow J_q^1$ is called bent if all the Fourier coefficients of w have unit magnitude. An interesting result shows that it is immaterial as to which particular complex, primitive, q^{th} root w, of unity is used in defining a bent function. The nature of the Fourier coefficients of a bent function is examined as a proof for the non-existence of bent functions over J_q^m, m odd, $q=2 \pmod 4$, given. For every other possible value of q and m, constructions of

bent functions are provided.

M. SPREAD SPECTRUM COMMUNICATIONS HISTORY

- Scholtz, R.A., "The Origins of Spread Spectrum Communications", IEEE Trans. on Communications, May 1982, pp. 822-854. (20 reprints sent with prior report)

This monograph review events, circa 1920-1960, leading to the development of spread-spectrum communication systems. The WWVB, Hush-Up, SLADES, PSC-A/Rake, CODOMAC, and ARC-50 systems are featured, along with a description of the prior art in secure communications, and introductions to other early spread-spectrum communication efforts. References to the available literature from this period are included.

N. SENSOR ARRAY PROCESSING

- Eisenhart, B.S. and Scholtz, R.A., "Coupled Phase-Tracking Loops for Retrodirective Array Systems," Proceedings of the National Telecommunications Conference, IEEE, December 1981, pp. D4.4.1-D4.4.7. (20 copies sent with prior report)

A method of coupling phase-locked loops in the element receivers of a retrodirective array is developed. Under certain linearizing assumptions it is shown that tracking-loop performance is comparable to that achieved by a single tracking-loop operating on the output of an ideal phased array antenna system.

O. APPROXIMATION OF SYSTEMS AND SIGNALS

- L. Pernebo and L.M. Silverman, "Balanced Systems and Model Reduction," Proc. 18th IEEE Conf. on Decision and Control, Dec. 12-14, 1979, pp. 805-807. (No Abstract) (30 copies

sent with prior report)

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- M. Bettayeb, L.M. Silverman, and M. G. Safonov, "Optimal Approximation of Continuous Time," Proc. IEEE Conference on Decision and Control, Dec. 1980, pp. 195-196. (30 copies sent with prior report)

In [1], the problem of optimally approximating a discrete-time system by a lower-order system was solved based on a remarkable theoretical result of Adamjan, Arov and Krein [2]. In this paper, we derive similar reduced models for continuous-time systems using a new approach based on the system structure of the finite dimensional model. Concrete algorithms are developed for finding approximations of any specified order. These approximations are optimal in a well defined sense.

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- S. Shokoohi, L.M. Silverman, and P. Van Dooren, "Stability of Balanced Time-Variable System Approximations," Proc. of the IEEE Conference on Decision and Control, Dec. 1980, pp. 500-503. (30 copies sent with prior report)

A uniformly balanced realization for time-varying systems is defined. Such a framework has many remarkable properties and leads to a natural setting for performing model reduction. It turns out that in many cases a reduced model preserves the properties of the original model. In this paper stability of the reduced systems is fully explored.

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- S. Shokoohi, L.M. Silverman, and P. Van Dooren, "Stable Approximation of Time-Variable Systems", Proc. of the IFAC, International Federation on Automatic Control, 1981, pp. 98-103. (20 copies sent with prior report)

The authors previously introduced the notion of a "uniformly balanced" realization for time-variable systems. This representation is characterized by the fact that its controllability and observability grammians are equal and diagonal. Such a framework has many remarkable properties and leads to a setting where the subsystems can be taken as reduced model for time-variable systems. It turns out that once the stability of a subsystem is guaranteed, then the subsystem preserves many of the properties of the original system. In this paper the stability of subsystems is fully explored.

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- S. Shokoohi and L.M. Silverman, "Model Reduction of Discrete Time-Variable Systems Via Balancing", Proc. of the 20th IEEE Conf. on Decision and Control, 1981, pp. 118-122. (20 copies sent with prior report)

Linear, discrete, time-variable systems are considered and an important class of uniform realizations is defined. The necessary and sufficient conditions for a pulse response to be uniformly realizable is obtained. Two model reduction schemes, one via balancing and the other via Hankel matrix are proposed. It is shown that the two approaches yield an identical reduced model which is always asymptotically stable.

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- E.A. Jonckheere, M.G. Safanov, and L.M. Silverman, "Topology Induced by the Hankel-Norm in the Space of Transfer Matrices", Proc. of the 20th IEEE Conf. on Decision and Control, 1981, pp. 118-122. (20 copies sent with prior report)

It is shown that the Hankel norm induces a topology in the space of transfer matrices which is too weak in general for studying stability of feedback systems.

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- B. Lasngari and L.M. Silverman, "Approximation of 2-D Weakly Causal Filters", IEEE Trans. on Circuits and Systems, vol. CAS-29, July 1982, pp. 482-486. (20 reprints sent with this report)

A technique for approximating 2-D weakly causal filters by recursive ones is presented which also includes the design of nonsymmetric half-plane (NSHP) filters. An example is given to illustrate the proposed technique.

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- S. Shokoohi, L.M. Silverman and P. Van Dooren, "Linear Time-Variable Systems: Balancing and Model Reduction", to appear in IEEE Trans. on Automatic Control. (1 preprint sent with this report)

A "uniformly balanced" realization for linear time-variable systems is defined. This representation is characterized by the fact that its controllability and observability grammians are equal and diagonal. Existence and uniqueness of the uniformly balanced realization is studied. Such a framework has many remarkable properties and leads to a novel method for approximating time-variable systems, where the

subsystems of the balanced realization can be taken as a reduced model. The reduced model is examined from the point of view of stability, controllability and observability.

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- B. Lashgari and L.M. Silverman, "Cascade Realization of 2-D Separable in Denominator Filters", to appear in Circuits, Systems and Signal Processing. (1 preprint enclosed with this report)

After selecting the most suitable model for the class of two-dimensional quarter-plane-causal, recursive, and separable in denominator (CRSD) filters, a procedure for realizing a cascade system of such filters is developed. The realization utilizes the individual CRSD Models constituting the cascade system. An example is given to further illustrate the technique.

P. CODE TRACKING OF SPREAD SPECTRUM WAVEFORMS

- A. Polydoros, and C.L. Weber, "On the Analysis and Optimization of Correlative Code Tracking Loops", IEEE Trans. on Communications. (Accepted for publication) (1 preprint sent with this report)

The purpose of this paper is to apply the renewal theory approach for analyzing aperiodic finite Z-curve code-tracking loops developed by Meyr [8] to the case of a noncoherent arbitrary offset early/late delay-locked-loop ("noncoherent d-DLL"). The exact (renewal) approach is compared with the approximate (periodic extension) approach of using the periodic S-curve or phase-locked-loop theory, as well as with the linear theory developed herein for the aforementioned

code-tracking loop. Finally, loop optimization with respect to the offset d is carried out according to performance criteria discussed in the Introduction. The results indicate that, for low SNR, the exact and approximate theories could deviate significantly while, for high SNR, all three theories yield identical performance, as expected. Furthermore, it is shown that the optimal d for both low and high SNR differs from the commonly accepted choice d=1/2.

Q. TRACKING OF DIGITALLY MODULATED SIGNALS

- C.L. Weber and W. Alem, "Demod-remod Coherent Tracking Receiver for QPSK and SQPSK, IEEE Trans. on Communications, Vol. COM-28, No. 12, pp. 1945-1954, Dec. 1980. (30 copies sent with prior report)

A demod-remod coherent tracking loop for QPSK and SQPSK is described and analyzed. This type receiver is attractive since all of the available signal power is despread and used to generate the tracking error signal when the pulses reaching the nonlinearities are rectangular. The same demod-remod circuit is widely used for bandlimited pulses, for which less than full power is converted to the carrier phase error signal.

All system parameters pertinent to system performance are enumerated. The effects of the IF and arm filters on the statistics of the noise are determined. With respect to the signal, the filters are considered only insofar as they reduce the delivered signal power. It is demonstrated how a tracking phase error converts some of the signal power into additional noise power. The results of performance computation are presented.

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- C.L. Weber and W.K. Alem, "Performance Analysis of Demod-Remod Coherent Receiver for QPSK and SQPSK Input", IEEE Trans. on Communications, Vol. Com-28, No. 8, pp. 1954-1968, December 1980. (30 copies sent with prior report)

A demod-remod coherent tracking loop for QPSK and SQPSK is described and analyzed in [1]. Those results are used to obtain the power spectral density of the equivalent noise of the tracking loop and the probability density function of the steady state phase error. The effects of the IF and arm filters on the statistics of the noise and QPSK signal are developed. The results of performance computations are presented.

B. PERFORMANCE OF SPREAD SPECTRUM SYSTEMS IN A MULTIPLE ACCESS ENVIRONMENT

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- C.L. Weber and G.K. Huth, "Performance Considerations of Code Division Multiple-Access Systems", IEEE Trans. on Vehicular Technology, Feb. 1981. (20 reprints sent with prior report)

The performance of code division multiple-access (CDMA) systems is determined using direct-sequence spectral spreading. Asynchronous users are assumed so that there is no network control. Under relatively ideal conditions, the degradation in system performance as a function of the number of users is shown to have a threshold effect. The basic limitation in the number of users of the system is further limited if the powers are unequal. For two users, system performance

as a function of their power ratios also has a threshold effect. System performance as a function of the amount of spectral spreading is determined. The performance of both coded and uncoded systems is predicted.

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– C.L. Weber and G.K. Huth, "Performance Considerations of Frequency Hopping Multiple Access", Proc. of the National Telecommunications Conference, pp. 09.4.1–09.4.5, Houston, Texas, Dec. 1980. (30 copies sent with prior report)

The basic system parameters of a frequency-hopping multiple-access system are investigated. Non-coherent binary FSK and M-ary FSK signal formats are studied in a random-access asynchronous environment. Both slow and fast frequency hopping are considered.

Under relatively ideal conditions, the degradation in performance with respect to the number of users is determined. The dependence on performance due to hopping rate and bandwidth constraint is developed. It is shown, for example, that, for fast hopping, the optimum hopping rate is that which spreads the users' power over the entire available bandwidth during each baud time. This agrees with the basic spread spectrum philosophy of making the signal appear white over a wide a bandwidth as possible.

The computational results describe the trade-off between the number of tones in M-ary FSK and the number of hops per symbol. Given a specified number of tones in the frequency-hopping system, the results describe the manner in which the system degrades a the number of users

is increased.

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- C.L. Weber, G.K. Huth and B.H. Batson, "Performance of Code-Division Multiple-Access Systems", Record of the International Conference on Communications, Seattle, Washington, June 1980, pp. 15.5.1-15.5.5. (30 copies sent with prior report)

The performance of code division multiple-access (CDMA) systems is determined using direct sequence spectral spreading. Under relatively ideal conditions, the degradation in system performance as a function of the number of users is shown to have a threshold effect. This basic limitation in the number of users of the system is further limited if the powers are unequal. For two users, system performance as a function of their power ratio also has a threshold effect. System performance as a function of the amount of spectral spreading is determined. The performance of both coded and uncoded systems is predicted.

5. ACQUISITION OF SPREAD SPECTRUM WAVEFORMS

- D.M. DiCarlo and C.L. Weber, "Statistical Performance of Single Dwell Serial Synchronization Systems", Proc. NTC '79, Washington, D.C., Nov. 26-29, 1979, pp. 24.2.1-5. (30 copies sent with prior report)

The probability of successful synchronization for a single dwell serial synchronization system is derived. This probability is a function of the number of cells searched and is expressed in terms of the following four parameters: the dwell per cell, the detection and false alarm probabilities and the penalty time for a false alarm.

Numerical results are presented to show the relationship between these parameters and system performance.

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– C.L. Weber and D.M. DiCarlo, "Multiple Dwell Serial Synchronization of Pseudonoise Signals", Proceedings of the International Communications Conference, IEEE, June 1981, pp. 34.4.1–5. (20 copies sent with prior report)

A generalized multiple dwell serial search technique suitable for coarse synchronization of pseudonoise signals is described. The advantage of the multiple dwell procedure is that the examination period need not be fixed, thus, incorrect alignments can be quickly discarded resulting in a shorter synchronization time than is possible with a fixed dwell time system.

Theoretical coherent detector characteristics are then used to investigate the performance of the multiple dwell serial synchronization technique for pseudonoise signals. It is shown that the multiple dwell technique can reduce the mean synchronization time and standard deviation by a factor of three from that obtained with a dwell system. It is also observed that the effects of a penalty time for a system false alarm can also be nearly eliminated by using the multiple dwell technique.

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– C.L. Weber and D. DiCarlo, "Statistical Performance of Single Dwell Serial Synchronization Systems", IEEE Trans. on Communications, Vol. COM-28, No. 8, pp. 1382–1388, Aug. 1980. (30 copies sent with prior report)

Single dwell serial search techniques are useful for coarse time and frequency synchronization of spread spectrum systems. A valuable system performance criterion, namely the probability of successful synchronization for a single dwell serial synchronization system is derived. The probability is a function of the number of cells searched and is expressed in terms of the following four parameters: the dwell per cell, the detection and false alarm probabilities and the penalty time for a false alarm. Numerical results are presented to show the relationship between these parameters and system performance.

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– D.M. DiCarlo and C.L. Weber, "Multiple Dwell Serial Acquisition of Direct Sequence Code Signals", IEEE Trans. on Communications, (Accepted for publication). (1 preprint sent with prior report)

The technique of multiple dwell serial search is described and analyzed. The advantage of the multiple dwell procedure is that the examination interval need not be fixed, allowing incorrect cells to be quickly discarded, which in turn results in a shorter search time than is possible with a fixed dwell time procedure. This type of search scheme is particularly useful for direct sequence code acquisition in a spread spectrum communication system.

An expression for the generating function is obtained from a flow graph representation of the multiple dwell technique. The generating function is used to develop expressions for the mean and variance of the search time in terms of the following parameters: the dwell

time, the detection probability, the false alarm probability, and the false alarm penalty time. Coherent detector characteristics are then used to investigate the performance of the multiple dwell technique for direct sequence code acquisition. It is shown that the multiple dwell procedure can significantly reduce the expected acquisition time from that obtained with a single dwell system.

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- A. Polydoros and C.L. Weber, "Rapid Acquisition Techniques for Direct-Sequence Spread Spectrum Systems Using an Analog Detector", Proceedings of the National Telecommunications Conference, IEEE, December 1981, pp. A7.1.1-5. (20 copies sent earlier)

A rapid acquisition scheme for Direct-Sequence Spread Spectrum systems (DS/SS) is described, whereby the rate of the "out-of-sync" decisions is an integer multiple of the code chip rate. The acquisition philosophy is briefly outlined and the overall scheme, employing an ideal (analog) detector, is analyzed with emphasis on the acquisition time statistics. Results show a strong dependence of performance on threshold settings and existing signal-to-noise ratio (SNR).

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- C.L. Weber and A. Polydoros, "Worst Case Considerations for Direct Sequence PN Acquisition", Proc. of the National Telecommunications Conference, pp. 24.6.1-5, Houston, Texas, Dec. 1980. (30 copies sent with prior report)

Worst-case detection conditions for coherent serial acquisition of PN sequences are determined. Signal-to-noise ratios (SNR) which are typical in the spread spectrum environments are considered. It is

shown that the worst-case correlation positions are dependent on only the correlator step size, but these positions are very sensitive to SNR. At very low SNR (-30 db), detection performance is essentially independent of correlation position whereas, at higher SNR (-20 dB), performance is very sensitive to correlator position. Both full-period and partial-period correlations are considered.

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- A. Polydoros and C.L. Weber, "A Unified Approach to Serial Search Acquisition of Direct Sequence Spread Spectrum Systems", IEEE Trans. on Communications. (Accepted for publication) (1 preprint sent with prior report)

The purpose of this paper is threefold: first to give an overview of the acquisition concept in spread spectrum systems by classifying the main features of the currently available techniques and by emphasizing the proper measures of overall system performance. Second, to provide a general framework for predicting the acquisition performance of systems with fixed dwell times. This is done by extending the previously suggested [2] approach to flow-graph techniques.

The statistics of acquisition time for the single dwell [2-3] and N-Dwell [5] examples are shown to be special cases of this unified approach to acquisition.

Finally, the general theory is applied to an example of a fast-decision-rate (matched filter) noncoherent acquisition receiver structure in a direct sequence spreading system. The results illustrate the dramatic dependence of the mean acquisition time on

system parameters.

T. BINARY SEQUENCES WITH MORE AUTOCORRELATION VALUES

- Wang Ke and L.R. Welch, "Binary Sequences with Non-Positive Autocorrelation Values", Acta Electronics Sinica, No. 10, October 1962, People's Republic of China. (1 preprint enclosed with this report)

Baumert developed the theory of binary sequences with the property of transorthogonality and orthogonality for cyclic shifts. Turyn investigated the existence of binary sequences with small autocorrelation values in terms of $\min \max |a|$ where a is the periodic correlation and the minimization is over binary sequences of fixed length. In this paper we restrict the invetigation to cyclic correlation and drop the absolute value sign in the minmax expression. There are a number of channels in which large magnitude negative correlations are not objectionable. (Signal design for a laser channel where the initial detector is an energy pulse detector can be formulated into the present context.)

In this study many binary sequences were found with autocorrelation properties in between transorthogonality and orthogonality. The most interesting sequences were those we named Yin-Yang sequences whose out of phase correlations are zero except for T equals to one half the period when the value is negative. Within this class, an infinite family is constructed.

An exhaustive list of binary sequences with non-positive out-of-phase autocorrelation for lengths 4,8,12,16,20,24,28,32,36,40 was obtained

by computer search and presented at the end of this paper.

D. SPECTRAL SHAPING BY REDUNDANCY

- K.-C. Liu, "General Method for Computing the Spectrum for Markov Chains where Waveforms are Probabilistic Functions of State Transitions), Ph.D. Dissertation, Department of Electrical Engineering, University of Southern California, June 1981. (1 copy sent with prior report)

In the design of digital communication systems, the analysis of signal spectra plays a very important role. This study is concerned with a digital system in which time is divided into intervals and in each interval a waveform associated with a message symbol is transmitted. The problems in our discussion are the selection of waveforms and message redundancies for reliable reception in a noisy channel and the selection of message and waveform structures so that they do not interfere with a secondary use of the signal such as establishing frequency and phase synchrony.

In this paper we will analyze several methods of inserting redundancy to minimize the spectral energy near zero frequency. When the resulting signal is modulated onto a carrier, the resulting signal will then have minimal interference on phase-lock-loop circuits which establish carrier phase coherence. The primary mathematical tool for this analysis will be the Markov processes with a finite number of states and constant transition probabilities. There are many problems for which the state space is very large and it is impractical to carry out a direct evaluation using the traditional methods. In this study we develop a practical method for computing a spectrum of Markov

chains where waveforms are probabilistic functions of state transitions. Using this method, the calculation procedures are greatly simplified for problems that once were considered as difficult tasks.

V. COMBINATORIAL SEARCHES FOR GOOD CODES

- J.S. Soh, Generation of Linear Block Codes by Combinatorial Algorithms, Ph.D. Dissertation, Department of Electrical Engineering, University of Southern California, August 1980. (1 copy submitted with earlier report)

This dissertation examines a combinatorial existence problem in coding theory which, on the face of it, is impractical to solve by computer search. And it develops ideas and techniques to bring the problem within the of practicality and at the same time find good error-correcting group codes in a sense that the codes exceed the Varsharmov-Gilbert lower bound in binary symmetric channel with r check bits and a minimum distance d among codewords.

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